

Demonstration of Precise Estimation of Polar Motion Parameters With the Global Positioning System: Initial Results

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Data from the Global Positioning System (GPS) have been used to determine precise polar motion estimates. Conservatively calculated formal errors of the GPS least-squares solution are approximately 10 cm. The GPS estimates agree with independently determined polar motion values from very long baseline interferometry (VLBI) at the 5-cm level. The data were obtained from a partial constellation of GPS satellites and from a sparse worldwide distribution of ground stations. The accuracy of the GPS estimates should continue to improve as more satellites and ground receivers become operational, and eventually a near-real-time GPS capability should be available. Because the GPS data are obtained and processed independently from the large radio antennas at the Deep Space Network (DSN), GPS estimation could provide very precise measurements of Earth orientation for calibration of deep space tracking data and could significantly relieve the ever-growing burden on the DSN radio telescopes to provide Earth platform calibrations.

I. Introduction

Precise navigation and tracking for high Earth orbiter and interplanetary missions require knowledge of certain Earth platform parameters, including Earth orientation. Earth orientation [1] parameters include the angle (and rate) of rotation of the Earth relative to a reference position, and the position of the solid crust and mantle relative to the axis of rotation. These parameters can vary unpredictably on a daily (or more frequent) basis due to interactions between the rotating solid Earth, its oceans, and atmosphere. By incorporating measurements made over

several days and by using a Kalman filter, it is possible to smooth and predict the longer-term components of Earth orientation. Presently, Earth orientation calibrations for deep-space tracking are made twice a week by using combinations of 70-m and 34-m antennas for very long baseline interferometry (VLBI) observations of quasar radio sources. Up to 10 hr per week can be required for this task for support of Magellan; similar demands are expected for the Galileo mission. Spacecraft telemetry communication is generally not possible when Deep Space Network (DSN) antennas are used for these Earth orientation observation sessions. Although the present-day VLBI technique ap-

pears sufficient to meet the 30-cm Magellan/Galileo-Earth orientation requirement (needed within about one day after the data are taken), the technique leaves less time available for direct spacecraft tracking. If interplanetary missions to the Moon, Mars, and other destinations occur later in the 1990s, as expected, DSN radio antennas will become increasingly busy, and antenna time will be at a premium.

A relatively new technique for monitoring Earth orientation incorporates data from the United States Global Positioning System (GPS), which presently includes about 15 navigation satellites, to be expanded to 18 by 1992, and further to 24 satellites by the mid-1990s. As described in [2], the GPS data will be combined with VLBI measurements. In this combined system, VLBI observations can be made with greatly reduced frequency from the present. The result of the combined GPS/VLBI system is expected to be an Earth orientation monitoring technique that can be made more accurate than the original VLBI system alone, but requires significantly less DSN radio antenna time. In addition to enhancing productivity of the DSN by enabling more time for direct spacecraft tracking and telemetry communication, the improved accuracy of the new system could help the DSN better support a sub-nanoradian deep-space tracking capability.

The DSN has installed advanced GPS terminals at each deep space tracking site for ionospheric calibrations.¹ Since the GPS transmits at two L-band frequencies, the lowest order ionospheric path delays can be determined straightforwardly at each site by using GPS data. These DSN GPS receivers will soon become the reference sites for a worldwide, high-precision GPS tracking network. The TOPEX/POSEIDON oceanography satellite, carrying its own GPS receiver, will be tracked with GPS differential techniques by this worldwide network. For several years, data from other, less precise worldwide GPS stations have been collected and processed. In order to test the capability of such networks to provide measurements of Earth orientation, data from one of the earliest worldwide GPS experiments in 1988 were processed to estimate X and Y polar motion parameters. The results of this test are reported in this article.

II. Experimental Data

The GPS experiment utilized for this study is described in [3] and [4]. To estimate Earth orientation parameters,

¹ C. J. Vegos, *DSCC Media Calibration Subsystem (DMD), Functional Design Review (Level D)*, JPL 834-30, vol. 1 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 1, 1987.

a three-day arc (January 19–21, 1988) was selected from the experiment, which spanned about three weeks. This particular three-day arc actually did not contain an optimal set of measurements, since one of the four fiducial (fixed reference) sites did not collect data on the first day. However, these data were the first to be processed and conveniently available for use. The four fiducial sites were all at VLBI observatories where precise coordinates were available: Hatcreek, California; Fort Davis, Texas; Haystack, Massachusetts; and Onsala, Sweden. The coordinates of the other sites were estimated from the GPS data: Wettzell, Germany; Canberra, Australia; Black Birch, New Zealand; Limón, Costa Rica; Liberia, Costa Rica; Cocos Island (off South America in the Pacific Ocean); Mojave, California; and Owens Valley, California. The data from these 12 stations represent less than half of the data actually collected over the three-day arc. Additional stations were left out in order to reduce the computational load, since all the GPS data were reduced on microcomputers. Figure 1 shows the location of the 12 sites used and the sparse worldwide coverage that was available. The satellite constellation in 1988 included only seven satellites, which provided only partial geometrical coverage.

III. Approach and Results

GPS-based positioning techniques generally involve a least-squares estimation of various parameters from the GPS data. For high-precision applications, such as the determination of Earth orientation, the parameters include the GPS orbits themselves. Other estimated parameters include nonfiducial station coordinates; relative clock offsets of GPS receivers and transmitters modeled as a white-noise process from measurement to measurement; zenith troposphere delays at each site, modeled as a random-walk stochastic process, with noise level of $(1.2 \text{ cm})^2/\text{hr}$; the Earth orientation polar motion parameters; and GPS carrier phase bias parameters. All parameters were estimated simultaneously.

The a priori uncertainties of all the parameters, other than the Earth orientation parameters, were very large, effectively infinite. The a priori uncertainty of the polar motion parameters was initially 50 cm. Since the final formal sigmas for these parameters ended up at the level of ~ 10 cm, the run was repeated with 200-cm a priori sigmas, but the solutions changed by less than 0.2 cm, confirming that the a priori sigmas for the polar motion parameters were not constraining the GPS solutions.

The solutions were determined with a square-root information filter. The method is described in [5–7]. The

data were compressed to 6-min intervals. Data weights used were 1 cm for the GPS carrier phase and 200 cm for the GPS pseudorange. As described in [8], the GPS carrier phase provides a very precise measure of range change but is ambiguous by an integer multiple of wavelengths. By processing together the phase and range data and by using an innovative technique developed for resolving the carrier phase ambiguities [8], most of the carrier phase biases in North and South America were resolved. Because of correlations between the phase biases and the clock parameters, resolving the ambiguities is possible only between pairs of stations and satellites. The greater the distance between the two stations, the more difficult it is to resolve ambiguities involving that pair. In principle, when carrier phase biases are resolved, solutions should improve significantly, since the ambiguous phase data (measuring *range change*) has been effectively converted to a very precise (subcentimeter) *range* measurement. One of the goals of this study was to examine the effect of GPS phase ambiguity techniques on the estimation of global Earth orientation parameters. Although ambiguity resolution has been known to dramatically improve the accuracy of baseline estimates [8], the effect on global Earth platform parameters has not been studied prior to the analysis presented in this article.

The results appear in Table 1. The differences between the GPS and VLBI (International Radio Interferometric Surveying, IRIS) estimates for X and Y polar motion are listed along with the formal errors from the GPS solution. Most (~70 percent) of the GPS formal errors, which are simply the parameter standard deviations from the covariance matrix, are from the computed error (data noise, geometry, and satellite visibility), with the remainder due to systematic error from an assumed 4-cm error for each fiducial station coordinate. The systematic fiducial coordinate errors were calculated from a consider analysis [9] and are probably conservative, since GPS and VLBI comparisons, at least in North America, have shown that the GPS fiducial coordinate errors are probably at the level of ~2 cm or better per coordinate [5]. Note that after ambiguity resolution, the GPS and VLBI Earth orientation estimates agree to 5 cm or better in each component.

IV. Discussion

The reader is cautioned that the comparison of polar motion parameters from GPS and VLBI techniques should be regarded as preliminary, since only a three-day GPS solution was used. However, previous results reported elsewhere [10] with somewhat cruder GPS orbit determination strategies have shown consistency between VLBI and GPS at the 10–20-cm level during a two-year period. The other

results [10] utilized a weaker GPS orbit solution, with ~5-m accuracy. The orbits reported here have been improved to the level of 60–100 cm [7] through careful modeling and orbit estimation techniques, so Earth orientation accuracy of ~5 cm is indeed consistent with results reported elsewhere when scaled for the different orbit accuracies (assuming that the errors are proportional).

The formal errors shown in Table 1 are large enough (~10 cm) so that there is no statistically significant difference between the GPS and VLBI polar motion estimates. In fact, the accuracy of the VLBI estimates themselves is presently believed to be ~3 cm, which is not much different from the 5-cm differences observed. The GPS–VLBI (IRIS) polar motion differences are actually a measure of the offset between the reference frame defined by the GPS fiducial site coordinates (which were held fixed in the solution) and the IRIS Earth orientation time series. Since both the fiducial site coordinates and the IRIS Earth orientation values were determined with VLBI, it might be expected a priori that the offset should be zero. However the fiducial site coordinates were obtained from a global Crustal Dynamics Project (CDP) VLBI solution (solution set GLB223 from Goddard Space Flight Center), which is not entirely consistent with the IRIS Earth orientation time series: an intercomparison in [11] showed that 1–3-cm discrepancies between independent VLBI solutions (CDP and IRIS) for polar motion are observed. Although the present GPS estimates are probably not sufficiently precise to detect this discrepancy, it is clear that a unified reference frame must be defined so that GPS Earth orientation estimates that incorporate VLBI fiducial coordinates can be related to VLBI estimates of Earth orientation.

Table 1 also shows a dramatic improvement in the accuracy of the GPS polar motion estimates with ambiguity resolution. This improvement is confirmed both in the formal calculated errors and in the comparison with independent VLBI estimates.² The result is intriguing since polar motion is essentially a global quantity, while GPS phase ambiguity resolution is most effective for shorter baselines. In fact, in this experiment, no ambiguities were resolved between the continents of North America and Europe (more than 5000 km apart), although most ambiguities of a few thousand kilometers or less over baselines in North and South America were resolved. Thus, ambiguity resolution within local continental networks was still able to significantly improve estimates of global quantities. This process can be understood in the context of

² Although the Y polar motion GPS–VLBI difference appears to be slightly worse, the difference is, in fact, statistically insignificant.

improving the GPS orbits through ambiguity resolution: even relatively short distance ambiguity resolution can improve the accuracy of the orbits. These improved orbits, in turn, result in better estimates for other, global parameter estimates. There may be implications for strategies to determine global Earth platform parameters with GPS if results, such as those in Table 1, are confirmed in future studies. By incorporating GPS data from a few stations relatively close (approximately hundreds to a few thousand kilometers) to the DSN fiducial GPS sites, GPS estimates of Earth orientation may be considerably enhanced. Data from these additional sites are fairly easy to acquire. For example, in California, there are dozens of GPS sites from which data are routinely collected by several U.S. Government agencies. Similar data are now or soon will be available from Europe and the South Pacific as GPS ground networks for various National Aeronautics and Space Administration (NASA) and international geodetic programs densify and GPS ground stations for other missions (such as TOPEX/POSEIDON and the Earth Observing System, EOS) became operational.

Other facets of GPS technology applicable to Earth orientation include the potential for a near-real-time capability and support for very high-precision (~ 1 nanoradian) VLBI deep space tracking/navigation. An advanced version of the DSN GPS Rogue receiver is in development that will automatically perform numerous data reduction steps in the receiver while the data are collected in the field.³ This would enable very fast data turnaround and the potential for routine delivery of Earth platform parameters the same (or next) day. Certain data types used by the DSN, such as differential Doppler, require accurate Earth orientation calibrations to achieve their full navigation potential.^{4,5} A GPS network in California is presently being tested for rapid production of GPS orbits and other related parameters. A recent test using receivers in California resulted in GPS orbits estimated in less than 24 hours after the data were acquired in the field. The ultra-precise (1-nanoradian or better) VLBI deep space tracking system currently being studied at JPL [12] under DSN Advanced Systems for future planetary missions

incorporates the estimation of Earth platform parameters in the course of multiple VLBI observations of quasars and spacecraft. Centimeter-level Earth orientation knowledge from GPS could constrain the a priori uncertainties in the Earth platform parameters to be further refined and improved from the VLBI data. Such a priori knowledge would enhance the performance of the system since it would require less data (and therefore fewer DSN resources) to achieve the desired accuracy.

As discussed in [2], GPS data can be quite sensitive to the rate of change of UT1-UTC, also known as the length of day. This information could be combined with relatively infrequent VLBI measurements of UT1-UTC to provide the DSN with a continuous and accurate record of UT1-UTC, a quantity that is needed along with polar motion for deep space navigation. However, the sparse ground coverage and relatively small number of satellites available during the 1988 GPS experiment hindered the determination of the length of day (the UT1-UTC rate), even with the three-day arc used. The three-day arc GPS estimate of the UT1-UTC rate had formal uncertainty of more than 5 cm/day. In future experiments with more satellites and ground stations operating, it should be possible to demonstrate a UT1-UTC rate accuracy of better than 1 cm/day along with accuracy for pole position improving to the level of 1-2 cm. One such experiment is expected to take place in early 1991.

V. Summary and Conclusions

An initial GPS solution for X and Y polar motion agrees with VLBI to better than 5 cm in each component. The GPS experiment was successful beyond expectations, with GPS-VLBI agreement better than the ~ 10 -cm-level predicted from the GPS solution covariance. Even more significant, perhaps, is the fact that the GPS solution was obtained with a somewhat sparse ground network tracking only seven GPS satellites, about one-third of the full GPS constellation, which is expected to be complete by 1992.

The GPS polar motion estimates improved significantly after GPS phase ambiguity resolution. This is the first demonstration that global Earth parameters estimated from GPS data improve when ambiguity resolution is performed, even though GPS ambiguity resolution is generally carried out over baselines much shorter than the radius of the Earth.

Further improvement in GPS polar motion estimates to the few-centimeter level is eventually expected as advanced

³ W. B. Melbourne, J. B. Thomas, C. L. Thornton, L. E. Young, and T. P. Yunck, *Turbo Rogue: The Next Generation GPS Geodetic Receiver* (internal document), Jet Propulsion Laboratory, Pasadena, California, November 9, 1989.

⁴ S. W. Thurman, "Deep-Space Navigation Performance of X-Band (8.4 GHz) Differenced Doppler Data," JPL Interoffice Memorandum 314-486 (internal document), Jet Propulsion Laboratory, Pasadena, California, July 24, 1990.

⁵ S. W. Thurman, "DSN Baseline Coordinate and Station Location Errors Induced by Earth Orientation Errors," JPL Interoffice Memorandum 314-488 (internal document), Jet Propulsion Laboratory, Pasadena, California, July 25, 1990.

DSN-type GPS receivers are installed worldwide, the GPS constellation begins to fill out, and the receivers are spread out more evenly around the globe. Additional GPS experiments are planned in the coming years to monitor this improvement, confirm the results reported in this article, and to demonstrate estimation of polar motion rates and the UT1-UTC rate with GPS.

The potential benefits to the DSN of using GPS for Earth platform parameter estimation are becoming clear with demonstrations of the inherently high precision and high data density that are available with GPS. The GPS

measurements can be combined with DSN VLBI observations to produce a time history of Earth orientation and rotation with high accuracy and high temporal resolution, requiring only a fraction of the antenna time that must presently be allocated to measure these quantities with VLBI alone. In addition to conserving DSN resources, GPS techniques could eventually result in a near-real-time estimation capability of Earth orientation for the DSN. The centimeter-level Earth orientation accuracy expected from the GPS data could also support and enhance an ultra-precise (subnanoradian) VLBI-based tracking and navigation system for the DSN.

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Table 1. Difference between GPS and VLBI Earth orientation estimates from January 19–21, 1988

Parameter	Initial GPS solution (no ambiguities resolved)	Final GPS solution (with ambiguity resolution)
X pole (σ formal error)	+16.3 cm (± 15)	-3.6 cm (± 8)
Y pole (σ formal error)	-2.0 cm (± 19)	-4.4 cm (± 12)

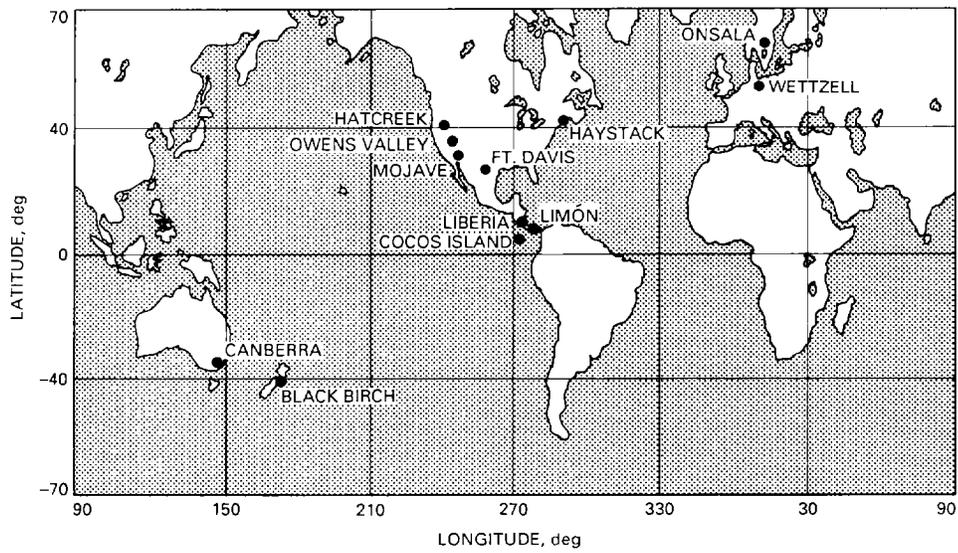


Fig. 1. Sites used in the 1988 worldwide GPS experiment for estimation of polar motion parameters.